

Exhibit B

astronomy

Main



science that encompasses the study of all extraterrestrial objects and phenomena. Until the invention of the telescope and the discovery of the laws of motion and gravity in the 17th century, astronomy was primarily concerned with noting and predicting the positions of the Sun, Moon, and planets, originally for calendrical and astrological purposes and later for navigational uses and scientific interest. The catalog of objects now studied is much broader and includes, in order of increasing distance, the solar system, the stars that make up the Milky Way Galaxy, and other, more distant galaxies. With the advent of scientific space probes, Earth also has come to be studied as one of the planets, though its more detailed investigation remains the domain of the geologic sciences.

The scope of astronomy

Since the late 19th century astronomy has expanded to include **astrophysics**, the application of physical and chemical knowledge to an understanding of the nature of celestial objects and the physical processes that control their formation, evolution, and emission of radiation. In addition, the gases and dust particles around and between the stars have become the subjects of much research. Study of the nuclear reactions that provide the energy radiated by stars has shown how the diversity of atoms found in nature can be derived from a universe that, following the first few minutes of its existence, consisted only of **hydrogen**, **helium**, and a trace of **lithium**. Concerned with phenomena on the largest scale is **cosmology**, the study of the evolution of the universe. Astrophysics has transformed cosmology from a purely speculative activity to a modern science capable of predictions that can be tested.

Its great advances notwithstanding, astronomy is still subject to a major constraint: it is inherently an observational rather than an experimental science. Almost all measurements must be performed at great distances from the objects of interest, with no control over such quantities as their temperature, pressure, or chemical composition. There are a few exceptions to this limitation—namely, **meteorites**, rock and soil samples brought back from the **Moon**, samples of **comet** dust returned by robotic spacecraft, and **interplanetary dust particles** collected in or above the stratosphere. These can be examined with laboratory techniques to provide information that cannot be obtained in any other way. In the future, space missions may return surface materials from Mars, asteroids, or other objects, but much of astronomy appears otherwise confined to Earth-based observations augmented by observations from orbiting satellites and long-range space probes and supplemented by theory.

The scope of astronomy » Determining astronomical distances

A central undertaking in astronomy is the determination of distances. Without a knowledge of its distance, the size of an observed object in space would remain nothing more than an angular diameter, and the brightness of a star could not be converted into its true radiated power, or luminosity. Astronomical distance measurement began with a knowledge of Earth's diameter, which provided a base for triangulation. Within the inner solar system, some distances can now be better determined through the timing of radar reflections or, in the case of the Moon, through laser ranging. For the outer planets, triangulation is still used. Beyond the solar system, distances to the closest **stars** are determined through triangulation, with the diameter of Earth's orbit serving as the baseline and shifts in stellar **parallax** being the measured quantities. Stellar distances are commonly expressed by astronomers in **parsecs** (pc), kiloparsecs, or megaparsecs. (1 pc = 3.086×10^{18} cm, or about 3.26 light-years [1.92×10^{13} miles].) Distances can be measured out to around a kiloparsec by trigonometric parallax (see **star: Determining stellar distances**). The accuracy of measurements made from Earth's surface is limited by atmospheric effects, but measurements made from the **Hipparcos satellite** in the 1990s have extended the scale to stars as far as 650 parsecs, with an accuracy of about a thousandth of an arc second. Less-direct measurements must be used for more-distant stars and for galaxies.

Two general methods for determining **galactic** distances are described here. In the first, a clearly identifiable type of star is used as a reference standard because its luminosity has been well determined. This requires observation of such stars that are close enough to Earth that their distances and luminosities have been reliably measured. Such a star is termed a "**standard candle**." Examples are **Cepheid variables**, whose brightness varies periodically in well-documented ways, and certain types of **supernova** explosions that have enormous brilliance and can thus be seen out to very great distances. Once the luminosities of such nearer standard candles have been calibrated, the distance to a farther standard candle can be calculated from its calibrated luminosity and its actual measured intensity. (The measured intensity [I] is related to the luminosity [L] and distance [d] by the formula $I = L/4\pi d^2$.) A standard candle can be identified by means of its spectrum or the pattern of regular variations in brightness. (Corrections may have to be made for the absorption of starlight by interstellar gas and dust over great distances.) This method forms the basis of measurements of distances to the closest galaxies.

The second method for galactic distance measurements makes use of the observation that the distances to galaxies generally correlate with the speeds with which those galaxies are receding from Earth (as determined from the Doppler shift in the



The scope of astronomy » Study of the solar system



The **solar system** took shape 4.57 billion years ago, when it condensed within a large cloud of gas and dust. Gravitational attraction holds the planets in their elliptical orbits around the **Sun**. In addition to **Earth**, five major planets (**Mercury**, **Venus**, **Mars**, **Jupiter**, and **Saturn**) have been known from ancient times. Since then only two more have been discovered: **Uranus** by accident in 1781 and **Neptune** in 1846 after a deliberate search following a theoretical prediction based on observed irregularities in the orbit of Uranus. **Pluto**, discovered in 1930 after a search for a planet predicted to lie beyond Neptune, was considered a major planet until 2006, when it was redesignated a **dwarf planet** by the International Astronomical Union.

The average Earth-Sun distance, which originally defined the **astronomical unit** (AU), provides a convenient measure for distances within the solar system. The astronomical unit is now defined dynamically (using Kepler's third law; see **Kepler's laws of planetary motion**) and has the value $1.49597870691 \times 10^{13}$ cm (about 93 million miles), with an uncertainty of about 2,000 cm. The mean radius of Earth's orbit is $1 + (3.1 \times 10^{-8})$ AU. Mercury, at 0.4 AU, is the closest planet to the Sun, while Neptune, at 30.1 AU, is the farthest. Pluto's orbit, with a mean radius of 39.5, is sufficiently eccentric that at times it is closer to the Sun than is Neptune. The planes of the planetary orbits are all within a few degrees of the **ecliptic**, the plane that contains Earth's orbit around the Sun. As viewed from far above Earth's North Pole, all planets move in the same (counterclockwise) direction in their orbits.

All of the planets apart from the two closest to the Sun (Mercury and Venus) have natural satellites (moons) that are very diverse in appearance, size, and structure, as revealed in close-up observations from long-range space probes. Pluto has at least three moons, including one fully half the size of Pluto itself. Four planets—Jupiter, Saturn, Uranus, and Neptune—have rings, disklike systems of small rocks and particles that orbit their parent planets.

Most of the mass of the solar system is concentrated in the Sun, with its 1.99×10^{33} grams. Together, all of the planets amount to 2.7×10^{30} grams (i.e., about one-thousandth of the Sun's mass), with Jupiter alone accounting for 71 percent of this amount. The solar system also contains a few known objects of intermediate size classified as dwarf planets and a very large number of much smaller objects collectively called **small bodies**. The small bodies, roughly in order of decreasing size, are the **asteroids**, or minor planets; **comets**, including **Kuiper belt** and **Oort cloud** objects; meteoroids (see **meteor and meteoroid**); and **interplanetary dust particles**. Because of their starlike appearance when discovered, the largest of these bodies were termed **asteroids**, and that name is widely used, but, now that the rocky nature of these bodies is understood, their more descriptive name is minor planets.

The four inner, terrestrial planets—Mercury, Venus, Earth, and Mars—along with the Moon have average densities in the range of 3.9–5.5 grams per cubic cm, setting them apart from the four outer, giant planets—Jupiter, Saturn, Uranus, and Neptune—whose densities are all close to 1 gram per cubic cm, the density of water. The compositions of these two groups of planets must therefore be significantly different. This dissimilarity is thought to be attributable to conditions that prevailed during the early development of the solar system (see *below Theories of origin*). Planetary temperatures now range from around 170 °C (330 °F, 440 K) on Mercury's surface through the typical 15 °C (60 °F, 290 K) on Earth to –135 °C (–210 °F, 140 K) on Jupiter near its cloud tops and down to –210 °C (–350 °F, 60 K) near Neptune's cloud tops. These are average temperatures; large variations exist between dayside and nightside for planets closest to the Sun, except for Venus with its thick atmosphere.

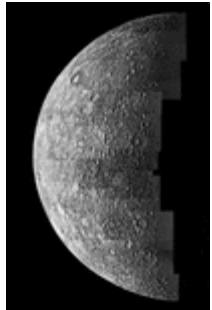
The surfaces of the terrestrial planets and many satellites show extensive cratering, produced by high-speed impacts (see **meteorite crater**). On Earth, with its large quantities of water and an active atmosphere, many of these cosmic footprints have eroded, but remnants of very large craters can be seen in aerial and spacecraft photographs of the terrestrial surface. On Mercury, Mars, and the **Moon**, the absence of water and any significant atmosphere has left the craters unchanged for billions of years, apart from disturbances produced by infrequent later impacts. Volcanic activity has been an important force in the shaping of the surfaces of the Moon and the terrestrial planets. Seismic activity on the Moon has been monitored by means of seismometers left on its surface by Apollo astronauts and by Lunokhod robotic rovers. Cratering on the largest scale seems to have ceased about three billion years ago, although on the Moon there is clear evidence for a continued cosmic drizzle of small particles, with the larger objects churning ("gardening") the lunar surface and the smallest producing microscopic impact pits in crystals in the lunar rocks.

The scope of astronomy » Study of the solar system » Lunar exploration

During the U.S. **Apollo** missions a total weight of 381.7 kg (841.5 pounds) of lunar material was collected; an additional 300 grams (0.66 pounds) was brought back by unmanned Soviet **Luna** vehicles. About 15 percent of the Apollo samples have been distributed for analysis, with the remainder stored at the NASA Johnson Space Center, Houston, Texas. The opportunity

see **Moon**

The scope of astronomy » Study of the solar system » Planetary studies



Mercury is too hot to retain an atmosphere, but **Venus**'s brilliant white appearance is the result of its being completely enveloped in thick clouds of carbon dioxide, impenetrable at visible wavelengths. Below the upper clouds, Venus has a hostile atmosphere containing clouds of sulfuric acid droplets. The cloud cover shields the planet's surface from direct sunlight, but the energy that does filter through warms the surface, which then radiates at infrared wavelengths. The long-wavelength infrared radiation is trapped by the dense clouds such that an efficient **greenhouse effect** keeps the surface temperature near 465 °C (870 °F, 740 K). Radar, which can penetrate the thick Venusian clouds, has been used to map the planet's surface. In contrast, the atmosphere of **Mars** is very thin and is composed mostly of carbon dioxide (95 percent), with very little water vapour; the planet's surface pressure is only about 0.006 that of **Earth**. The outer planets have atmospheres composed largely of light gases, mainly hydrogen and helium.

Each planet rotates on its axis, and nearly all of them rotate in the same direction—counterclockwise as viewed from above the ecliptic. The two exceptions are Venus, which rotates in the clockwise direction beneath its cloud cover, and **Uranus**, which has its rotation axis very nearly in the plane of the ecliptic.

Some of the planets have **magnetic fields**. Earth's field extends outward until it is disturbed by the **solar wind**—an outward flow of protons and electrons from the Sun—which carries a magnetic field along with it. Through processes not yet fully understood, particles from the solar wind and galactic **cosmic rays** (high-speed particles from outside the solar system) populate two doughnut-shaped regions called the **Van Allen radiation belts**. The inner belt extends from about 1,000 to 5,000 km (600 to 3,000 miles) above Earth's surface, and the outer from roughly 15,000 to 25,000 km (9,300 to 15,500 miles). In these belts, trapped particles spiral along paths that take them around Earth while bouncing back and forth between the Northern and Southern hemispheres, with their orbits controlled by Earth's magnetic field. During periods of increased solar activity, these regions of trapped particles are disturbed, and some of the particles move down into Earth's atmosphere, where they collide with atoms and molecules to produce **auroras**.

Jupiter has a magnetic field far stronger than Earth's and many more trapped electrons, whose **synchrotron radiation** (electromagnetic radiation emitted by high-speed charged particles that are forced to move in curved paths, as under the influence of a magnetic field) is detectable from Earth. Bursts of increased radio emission are correlated with the position of **Io**, the innermost of the four Galilean moons of Jupiter. **Saturn** has a magnetic field that is much weaker than Jupiter's, but it too has a region of trapped particles. Mercury has a weak magnetic field that is only about 1 percent as strong as Earth's and shows no evidence of trapped particles. **Uranus** and **Neptune** have fields that are less than one-tenth the strength of Saturn's and appear much more complex than that of Earth. No field has been detected around Venus or Mars.

The scope of astronomy » Study of the solar system » Investigations of the smaller bodies



More than 125,000 **asteroids** with well-established orbits are known, and several hundred additional objects are discovered each year. Hundreds of thousands more have been seen, but their orbits have not been as well-determined. It is estimated that several million asteroids exist, but most are small, and their combined mass is estimated to be less than a thousandth that of Earth. Most of the asteroids have orbits close to the ecliptic and move in the **asteroid belt**, between 2.3 and 3.3 AU from the Sun. Because some asteroids travel in orbits that can bring them close to Earth, there is a possibility of a collision that could have devastating results (see **Earth impact hazard**).

Comets are considered to come from a vast reservoir, the **Oort cloud**, orbiting the Sun at distances of 20,000–50,000 AU or more and containing trillions of icy objects—latent comet nuclei—with the potential to become active comets. Many comets have been observed over the centuries. Most make only a single pass through the inner solar system, but some are deflected by Jupiter or Saturn into orbits that allow them to return at predictable times. **Halley's Comet** is the best-known of these periodic comets, with its next return into the inner solar system predicted for ad 2061. Many short-period comets are thought to come from the **Kuiper belt**, a region lying mainly between 30 AU and 50 AU from the Sun—beyond Neptune's orbit but including part of Pluto's—and housing perhaps hundreds of millions of comet nuclei. Comet masses have not been well determined, but most are probably less than 10^{18} grams, one billionth the mass of Earth.

Since the 1990s hundreds of comet nuclei in the Kuiper belt have been observed with large telescopes; a few are about half the size of Pluto, and at least one, **Eris**, is estimated to be slightly larger. Pluto's orbital and physical characteristics had long caused it to be regarded as an anomaly among the planets, and, after the discovery of numerous other Pluto-like objects beyond Neptune, Pluto was seen to be no longer unique in its “neighbourhood” but rather a giant member of the local population. Consequently, in 2006 astronomers at the general assembly of the International Astronomical Union elected to create the new category of **dwarf planets** for objects with such qualifications. Pluto, Eris, and **Ceres**, the latter being the largest member of the asteroid belt, were given this distinction.

meteorite

Meteorites are classified into three broad groups: stony (chondrites and achondrites; about 94 percent), iron (5 percent), and stony-iron (1 percent). Most meteoroids that enter the atmosphere heat up sufficiently to glow and appear as meteors (see **meteor** and **meteoroid**), and the great majority of these vaporize completely or break up before they reach the surface. Many, perhaps most, meteors occur in showers (see **meteor shower**) and follow orbits that seem to be identical with those of certain comets, thus pointing to a cometary origin. For example, each May, when Earth crosses the orbit of Halley's Comet, the Eta Aquarid meteor shower occurs. Micrometeorites (**interplanetary dust particles**), the smallest meteoroidal particles, can be detected from Earth-orbiting satellites or collected by specially equipped aircraft flying in the stratosphere and returned for laboratory inspection. Since the late 1960s numerous meteorites have been found in the Antarctic on the surface of stranded ice flows (see **Antarctic meteorites**). Detailed analyses have shown that some of these meteorites have come from the Moon and others from Mars. Yet others contain microscopic crystals whose isotopic proportions are unique and appear to be dust grains that formed in the atmospheres of different stars.

The scope of astronomy » Study of the solar system » Determinations of age and chemical composition

The age of the solar system, taken to be close to 4.6 billion years, has been derived from measurements of radioactivity in meteorites, lunar samples, and Earth's crust. Abundances of isotopes of uranium, thorium, and rubidium and their decay products, lead and strontium, are the measured quantities.

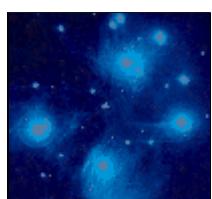
Assessment of the chemical composition of the solar system is based on data from Earth, the Moon, and meteorites as well as on the spectral analysis of light from the Sun and planets. In broad outline, the solar system abundances of the chemical elements decrease with increasing atomic weight. Hydrogen atoms are by far the most abundant, constituting 91 percent; helium is next, with 8.9 percent; and all other types of atoms together amount to only 0.1 percent.

The scope of astronomy » Study of the solar system » Theories of origin

The origin of Earth, the Moon, and the solar system as a whole is a problem that has not yet been settled in detail. The Sun probably formed by condensation of the central region of a large cloud of gas and dust, with the planets and other bodies of the solar system forming soon after, their composition strongly influenced by the temperature and pressure gradients in the evolving **solar nebula**. Less-volatile materials could condense into solids relatively close to the Sun to form the terrestrial planets. The abundant, volatile lighter elements could condense only at much greater distances to form the giant gas planets. After the early 1990s astronomers confirmed that stars other than the Sun have one or more planetlike objects revolving around them. Studies of the properties of these solar systems have both supported and challenged astronomers' theoretical models of how Earth's solar system formed. (See also **solar system: Origin of the solar system**.)

The origin of the planetary satellites is not entirely settled. As to the origin of the Moon, the opinion of astronomers had long oscillated between theories that saw its origin and condensation simultaneous with formation of Earth and those that posited a separate origin for the Moon and its later capture by Earth's gravitational field. Similarities and differences in abundances of the chemical elements and their isotopes on Earth and Moon had challenged each group of theories. Finally, in the 1980s a model emerged that has gained the support of most lunar scientists—that of a large impact on Earth with the expulsion of material that subsequently formed the Moon. (See **Moon: Origin and evolution**.) For the outer planets with their multiple satellites, many very small and quite unlike one another, the picture is less clear. Some of these moons have relatively smooth icy surfaces, whereas others are heavily cratered; at least one, Jupiter's Io, is volcanic. Some of the moons may have formed along with their parent planets, and others may have formed elsewhere and been captured. (For additional discussion of the solar system and its components, see **cosmos: Planetary systems**.)

The scope of astronomy » Study of the stars » Measuring observable stellar properties



The measurable quantities in stellar astrophysics include the externally observable features of the **stars**: distance, temperature, radiation spectrum and luminosity, composition (of the outer layers), diameter, mass, and variability in any of these. Theoretical astrophysicists use these observations to model the structure of stars and to devise theories for their formation and evolution. Positional information can be used for dynamical analysis, which yields estimates of stellar masses.

In a system dating back at least to the Greek astronomer-mathematician Hipparchus in the 2nd century bc, apparent stellar brightness (m) is measured in **magnitudes**. Magnitudes are now defined such that a first-magnitude star is 100 times brighter than a star of sixth magnitude. The human eye cannot see stars fainter than about sixth magnitude, but modern instruments used with large telescopes can record stars as faint as about 30th magnitude. By convention, the **absolute magnitude** (M) is defined as the magnitude that a star would appear to have if it were located at a standard distance of 10 parsecs. These quantities are related through the expression $m - M = 5 \log_{10} r - 5$, in which r is the star's distance in parsecs.

The magnitude scale is anchored on a group of standard stars. An absolute measure of radiant power is **luminosity**, usually expressed in ergs per second (ergs/sec). (Sometimes the luminosity is stated in terms of the solar luminosity, 3.86×10^{33} ergs/sec.) Luminosity can be calculated when m and r are known. Correction might be necessary for the interstellar absorption

There are several methods for measuring a star's diameter. From the brightness and distance the luminosity (L) can be calculated, and from observations of the brightness at different wavelengths the temperature (T) can be calculated. Because the radiation from many stars can be well approximated by a Planck blackbody spectrum (see **Planck's radiation law**), these measured quantities can be related through the expression $L = 4\pi R^2\sigma T^4$, thus providing a means of calculating R , the star's radius. In this expression, σ is the Stefan-Boltzmann constant, 5.67×10^{-5} ergs/cm²K⁴sec, in which K is the temperature in Kelvins. (The radius R refers to the star's photosphere, the region where the star becomes effectively opaque to outside observation.) Stellar angular diameters can be measured through interference effects. Alternatively, the intensity of the starlight can be monitored during **occultation** by the Moon, which produces diffraction fringes whose pattern depends on the angular diameter of the star. Stellar angular diameters of several milliarcseconds can be measured, but so far only for relatively bright and close stars.

Many stars occur in **binary systems** (see **binary star**), with the two partners in orbits around their mutual centre of mass. Such a system provides the best measurement of stellar masses. The period (P) of a binary system is related to the masses of the two stars (m_1 and m_2) and the orbital semimajor axis (mean radius; a) via Kepler's third law: $P^2 = 4\pi^2 a^3/G(m_1 + m_2)$, (G is the universal gravitational constant.) From diameters and masses, average values of the stellar density can be calculated and thence the central pressure. With the assumption of an **equation of state**, the central temperature can then be calculated. For example, in the **Sun** the central density is 158 grams per cubic cm; the pressure is calculated to be more than one billion times the pressure of Earth's atmosphere at sea level and the temperature around 15 million K (27 million °F). At this temperature, all atoms are ionized, and so the solar interior consists of a **plasma**, an ionized gas with hydrogen nuclei (i.e., protons), helium nuclei, and electrons as major constituents. A small fraction of the hydrogen nuclei possess sufficiently high speeds that, on colliding, their electrostatic repulsion is overcome, resulting in the formation, by means of a set of fusion reactions, of helium nuclei and a release of energy (see **proton-proton cycle**). Some of this energy is carried away by **neutrinos**, but most of it is carried by **photons** to the surface of the Sun to maintain its luminosity.

Other stars, both more and less massive than the Sun, have broadly similar structures, but the size, central pressure and temperature, and fusion rate are functions of the star's mass and composition. The stars and their internal fusion (and resulting luminosity) are held stable against collapse through a delicate balance between the inward pressure produced by gravitational attraction and the outward pressure supplied by the photons produced in the fusion reactions.

Stars that are in this condition of hydrostatic equilibrium are termed **main-sequence stars**, and they occupy a well-defined band on the **Hertzsprung-Russell (H-R) diagram**, in which luminosity is plotted against colour index or temperature. Spectral classification, based initially on the colour index, includes the major spectral types O, B, A, F, G, K and M, each subdivided into 10 parts (see **star: Stellar spectra**). Temperature is deduced from broadband spectral measurements in several standard wavelength intervals. Measurement of apparent magnitudes in two spectral regions, the B and V bands (centred on 4350 and 5550 angstroms, respectively), permits calculation of the **colour index**, $Cl = m_B - m_V$, from which the temperature can be calculated.

For a given temperature, there are stars that are much more luminous than main-sequence stars. Given the dependence of luminosity on the square of the radius and the fourth power of the temperature (R^2T^4 of the luminosity expression above), greater luminosity implies larger radius, and such stars are termed **giant stars** or **supergiant stars**. Conversely, stars with luminosities much less than those of main-sequence stars of the same temperature must be smaller and are termed **white dwarf stars**. Surface temperatures of white dwarfs typically range from 10,000 to 12,000 K (18,000 to 21,000 °F), and they appear visually as white or blue-white.

The strength of spectral lines of the more abundant elements in a star's atmosphere allows additional subdivisions within a class. Thus, the Sun, a main-sequence star, is classified as G2 V, in which the V denotes main sequence. **Betelgeuse**, a red giant with a surface temperature about half that of the Sun but with a luminosity of about 10,000 solar units, is classified as M2 Iab. In this classification, the spectral type is M2, and the Iab indicates a giant, well above the main sequence on the H-R diagram.

The scope of astronomy » Study of the stars » Star formation and evolution



The range of physically allowable masses for stars is very narrow. If the star's mass is too small, the central temperature will be too low to sustain fusion reactions. The theoretical minimum stellar mass is about 0.08 solar mass. An upper theoretical limit of approximately 100 solar masses has been suggested, but this value is not firmly defined. Stars as massive as this will have luminosities about one million times greater than that of the Sun.

A general model of star formation and evolution has been developed, and the major features seem to be established. A large cloud of gas and dust can contract under its own gravitational attraction if its temperature is sufficiently low. As gravitational energy is released, the contracting central material heats up until a point is reached at which the outward radiation pressure balances the inward gravitational pressure, and contraction ceases. Fusion reactions take over as the star's primary source of energy, and the star is then on the main sequence. The time to pass through these formative stages and onto the main sequence is less than 100 million years for a star with as much mass as the Sun. It takes longer for less massive stars and a much shorter time for those much more massive.

Once a star has reached its main-sequence stage, it evolves relatively slowly, fusing **hydrogen** nuclei in its core to form

Stellar evolution has of necessity been followed through computer modeling because the timescales for most stages are generally too extended for measurable changes to be observed, even over a period of many years. One exception is the **supernova**, the violently explosive finale of certain stars. Different types of supernovas can be distinguished by their spectral lines and by changes in luminosity during and after the outburst. In Type Ia, a **white dwarf star** attracts matter from its nearby companion; when the white dwarf's mass exceeds about 1.4 solar masses, the star implodes and is completely destroyed. Type II supernovas are not as luminous as Type Ia and are the final evolutionary stage of stars more massive than about eight solar masses.

The nature of the final products of stellar evolution depend on stellar mass. Some stars pass through an unstable stage in which their dimensions, temperature, and luminosity change cyclically over periods of hours or days. These so-called **Cepheid variables** serve as standard candles for distance measurements (see above **Determining astronomical distances**). Some stars blow off their outer layers to produce **planetary nebulae**. The expanding material can be seen glowing in a thin shell as it disperses into the interstellar medium, while the remnant core, initially with a surface temperature as high as 100,000 K (180,000 °F), cools to become a white dwarf. The maximum stellar mass that can exist as a white dwarf is about 1.4 solar masses and is known as the **Chandrasekhar limit**. More-massive stars may end up as either **neutron stars** or **black holes**.

The average density of a white dwarf is calculated to exceed one million grams per cubic cm. Further compression is limited by a quantum condition called degeneracy (see **degenerate gas**), in which only certain energies are allowed for the electrons in the star's interior. Under sufficiently great pressure, the electrons are forced to combine with protons to form neutrons. The resulting **neutron star** will have a density in the range of 10^{14} – 10^{15} grams per cubic cm, comparable to the density within atomic nuclei. The behaviour of large masses having nuclear densities is not yet sufficiently understood to be able to set a limit on the maximum size of a neutron star, but it is thought to be in the region of three solar masses.

Still more-massive remnants of stellar evolution would have smaller dimensions and would be even denser than neutron stars. Such remnants are conceived to be **black holes**, objects so compact that no radiation can escape from within a characteristic distance called the **Schwarzschild radius** (see **gravitational radius**). This critical dimension is defined by $R_s = 2GM/c^2$ (R_s is the Schwarzschild radius, G is the gravitational constant, M is the object's mass, and c is the speed of light.) For an object of three solar masses, the Schwarzschild radius would be about three kilometres. Radiation emitted from beyond the Schwarzschild radius can still escape and be detected.

Although no light can be detected coming from within a black hole, the presence of a black hole may be manifested through the effects of its gravitational field, as, for example, in a binary star system. If a black hole is paired with a normal visible star, it may pull matter from its companion toward itself. This matter is accelerated as it approaches the black hole and becomes so intensely heated that it radiates large amounts of X-rays from the periphery of the black hole before reaching the Schwarzschild radius. A few candidates for stellar black holes have been found—e.g., the X-ray source Cygnus X-1. Each of them has an estimated mass clearly exceeding that allowable for a neutron star, a factor crucial in the identification of possible black holes. (Supermassive black holes that do not originate as individual stars are thought to exist at the centres of active galaxies; see below **Study of other galaxies and related phenomena**.)

Whereas the existence of stellar black holes has been strongly indicated, the existence of neutron stars was confirmed in 1968 when they were identified with the then newly discovered **pulsars**, objects characterized by the emission of radiation at short and extremely regular intervals, generally between 1 and 1,000 pulses per second and stable to better than a part per billion. Pulsars are considered to be rotating neutron stars, remnants of some supernovas. (For additional discussion of stars and stellar evolution, see **cosmos: Stars and the chemical elements**.)

The scope of astronomy » Study of the Milky Way Galaxy



Stars are not distributed randomly throughout space. Many stars are in systems consisting of two or three members separated by less than 1,000 AU. On a larger scale, **star clusters** may contain many thousands of stars. **Galaxies** are much larger systems of stars and usually include clouds of gas and dust.

The solar system is located within the **Milky Way Galaxy**, close to its equatorial plane and about 8.7 kiloparsecs from the galactic centre. The galactic diameter is about 30 kiloparsecs, as indicated by

luminous matter. There is evidence, however, for nonluminous matter—so-called **dark matter** (see **cosmos: Dark matter**)—extending out nearly twice this distance. The entire system is rotating such that, at the position of the Sun, the orbital speed is about 220 km per second (almost 500,000 miles per hour) and a complete circuit takes roughly 240 million years. Application of Kepler's third law leads to an estimate for the galactic mass of about 100 billion solar masses. The rotational velocity can be measured from the Doppler shifts (see **Doppler effect**) observed in the 21-cm emission line of neutral hydrogen and the lines of millimetre wavelengths from various molecules, especially carbon monoxide. At great distances from the galactic centre, the rotational velocity does not drop off as expected but rather increases slightly. This behaviour appears to require a much larger galactic mass than can be accounted for by the known (luminous) matter. Additional evidence for the presence of dark matter comes from a variety of other observations. The nature and extent of the dark matter (or missing mass) constitutes one of today's major astronomical puzzles.

There are about 100 billion stars in the Milky Way Galaxy. Star concentrations within the galaxy fall into three types: open

Stellar association

Globular cluster

The scope of astronomy » Study of the Milky Way Galaxy » Investigations of interstellar matter

The **interstellar medium**, composed primarily of gas and dust, occupies the regions between the stars. On average, it contains less than one atom in each cubic centimetre, with about 1 percent of its mass in the form of minute dust grains. The gas, mostly **hydrogen**, has been mapped by means of its 21-cm emission line. The gas also contains numerous molecules. Some of these have been detected by the visible-wavelength absorption lines that they impose on the spectra of more-distant stars, while others have been identified by their own emission lines at millimetre wavelengths. Many of the interstellar molecules are found in giant molecular clouds, wherein complex **organic** molecules have been discovered.

In the vicinity of a very hot O- or B-type star, the intensity of ultraviolet radiation is sufficiently high to ionize the surrounding hydrogen out to a distance as great as 100 parsecs to produce an **H II region**, known as a Strömgren sphere. Such regions are strong and characteristic emitters of radiation at radio wavelengths, and their dimensions are well calibrated in terms of the luminosity of the central star. Using radio interferometers, astronomers are able to measure the angular diameters of H II regions even in some external galaxies and can thereby deduce the great distances to those remote systems. This method can be used for distances up to about 30 megaparsecs. (For additional information on H II regions, see **nebula: Diffuse nebulae (H II regions)**.)

Interstellar dust grains (see **nebula: Interstellar dust**) scatter and absorb starlight, with the effect being roughly inversely proportional to wavelength from the infrared to the near ultraviolet. As a result, stellar spectra tend to be reddened. Absorption amounts typically to about one magnitude per kiloparsec but varies considerably in different directions. Some dusty regions contain silicate materials, identified by a broad absorption feature around a wavelength of 10 μm . Other prominent spectral features in the infrared range have been sometimes, but not conclusively, attributed to graphite grains and polycyclic aromatic hydrocarbons.

Starlight often shows a small degree of **polarization** (a few percent), with the effect increasing with stellar distance. This is attributed to the scattering of the starlight from dust grains that have been partially aligned in a weak interstellar magnetic field. The strength of this field is estimated to be a few microgauss, very close to the strength inferred from observations of nonthermal cosmic radio noise. This radio background has been identified as synchrotron radiation, emitted by cosmic-ray electrons traveling at nearly the speed of light and moving along curved paths in the interstellar magnetic field. The spectrum of the cosmic radio noise is close to what is calculated on the basis of measurements of the **cosmic rays** near Earth.

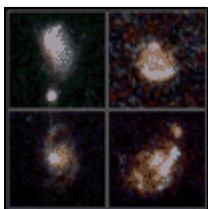
Cosmic rays constitute another component of the interstellar medium. Cosmic rays that are detected in the vicinity of Earth comprise high-speed nuclei and electrons. Individual particle energies, expressed in electron volts (eV; 1 eV = 1.6×10^{-12} erg), range with decreasing numbers from about 10^6 eV to more than 10^{20} eV. Among the nuclei, hydrogen nuclei are the most plentiful at 86 percent, helium nuclei next at 13 percent, and all other nuclei together at about 1 percent. Electrons are about 2 percent as abundant as the nuclear component. (The relative numbers of different nuclei vary somewhat with kinetic energy, while the electron proportion is strongly energy-dependent.)

A minority of cosmic rays detected in Earth's vicinity are produced in the Sun, especially at times of increased solar activity (as indicated by **sunspots** and **solar flares**). The origin of galactic cosmic rays has not yet been conclusively identified, but they are thought to be produced in stellar processes such as supernova explosions, perhaps with additional acceleration occurring in the interstellar regions. (For additional information on interstellar matter, see **Milky Way Galaxy: The general interstellar medium** and **cosmos: Interstellar clouds**; for additional information on cosmic rays and galactic nonthermal radio emission, see **cosmos: Cosmic rays and magnetic fields**.)

The scope of astronomy » Study of the Milky Way Galaxy » Observations of the galactic centre

The central region of the **Milky Way Galaxy** is so heavily obscured by dust that direct observation has become possible only with the development of astronomy at nonvisual wavelengths—namely, radio, infrared, and, more recently, X-ray and gamma-ray wavelengths. Together, these observations have revealed a nuclear region of intense activity, with a large number of separate sources of emission and a great deal of dust. Detection of gamma-ray emission at a line energy of 511,000 eV, which corresponds to the annihilation of electrons and **positrons** (the **antimatter** counterpart of electrons), along with radio mapping of a region no more than 20 AU across, points to a very compact and energetic source, designated **Sagittarius A***, at the centre of the galaxy (see **Sagittarius A**). Whether this source is powered by a supermassive black hole or some very close and hot stars remains to be determined. (For additional information on the Milky Way Galaxy, see **cosmos: The Milky Way Galaxy**.)

The scope of astronomy » Study of other galaxies and related phenomena



Spiral galaxies—of which the Milky Way system is a characteristic example—tend to be flattened, roughly circular systems with their constituent stars strongly concentrated along spiral arms. These arms are thought to be produced by traveling density waves, which compress and expand the galactic material. (For an explanation of the density wave theory, see **cosmos: Dynamics of ellipticals and spirals**.) Between the spiral arms exists a diffuse interstellar medium of gas and dust, mostly at very low temperatures (below 100 K [−280 °F, −170 °C]). Spiral galaxies are typically a few kiloparsecs in thickness; they have a central bulge and taper gradually toward the outer edges.

Ellipticals show none of the spiral features but are more densely packed stellar systems. They range in shape from nearly spherical to very flattened and contain little interstellar matter. **Irregular galaxies** number only a few percent of all stellar systems and exhibit none of the regular features associated with spirals or ellipticals.

Properties vary considerably among the different types of galaxies. Spirals typically have masses in the range of a billion to a trillion solar masses, with ellipticals having values from 10 times smaller to 10 times larger and the irregulars generally 10–100 times smaller. Visual galactic luminosities show similar spreads among the three types, but the irregulars tend to be less luminous. In contrast, at radio wavelengths the maximum luminosity for spirals is usually 100,000 times less than for ellipticals or irregulars.

Quasars are objects whose spectra display very large redshifts, thus implying (in accordance with the Hubble law) that they lie at the greatest distances (see above **Determining astronomical distances**). They were discovered in 1963 but remained enigmatic for many years. They appear as starlike (i.e., very compact) sources of radio waves—hence their initial designation as quasi-stellar radio sources, a term later shortened to *quasars*. They are now considered to be the exceedingly luminous cores of distant galaxies. These energetic cores, which emit copious quantities of X-rays and gamma rays, are termed active galactic nuclei and include the object **Cygnus A** and the nuclei of a class of galaxies called **Seyfert galaxies**. They may be powered by the infall of matter into supermassive black holes (see **cosmos: Black-hole model for active galactic nuclei**).

The Milky Way Galaxy is one of the **Local Group** of galaxies, which contains more than three dozen members and extends over a volume about one megaparsec in diameter. Two of the closest members are the **Magellanic Clouds**, irregular galaxies about 50 kiloparsecs away. At about 740 kiloparsecs the **Andromeda Galaxy** is one of the most distant in the Local Group. Some members of the group are moving toward the Milky Way system, while others are traveling away from it. At greater distances all galaxies are moving away from the Milky Way Galaxy. Their speeds (as determined from the redshifted wavelengths in their spectra) are generally proportional to their distances. The Hubble law relates these two quantities (see above **Determining astronomical distances**). In the absence of any other method, the Hubble law continues to be used for distance determinations to the farthest objects—that is, galaxies and quasars for which redshifts can be measured. (For additional information on external galaxies, see **cosmos: Galaxies**.)

The scope of astronomy » Cosmology

Cosmology is the scientific study of the **universe** as a unified whole, from its earliest moments through its evolution to its ultimate fate. The currently accepted cosmological model is the **big bang**. In this picture, the expansion of the universe started in an intense explosion about 10–20 billion years ago. In this primordial fireball, the temperature exceeded one trillion K, and most of the energy was in the form of radiation. As the expansion proceeded (accompanied by cooling), the role of the radiation diminished, and other physical processes dominated in turn. Thus, after about three minutes, the temperature had dropped to the one-billion-K range, making it possible for nuclear reactions of protons to take place and produce nuclei of deuterium and helium. (At the higher temperatures that prevailed earlier, these nuclei would have been promptly disrupted by high-energy photons.) With further expansion, the time between nuclear collisions had increased and the proportion of deuterium and helium nuclei had stabilized. After a few hundred thousand years, the temperature must have dropped sufficiently for electrons to remain attached to nuclei to constitute atoms. Galaxies are thought to have begun forming after a few million years, but this stage is very poorly understood. Star formation probably started much later, after at least a billion years, and the process continues today.

Observational support for this general model comes from several independent directions. The expansion has been documented by the redshifts observed in the spectra of galaxies. Furthermore, the radiation left over from the original fireball would have cooled with the expansion. Confirmation of this relic energy came in 1965 with one of the most striking cosmic discoveries of the 20th century—the observation, at short radio wavelengths, of a widespread cosmic radiation corresponding to a temperature of almost 3 K (about −454 °F or −270 °C). The shape of the observed spectrum is an excellent fit to the theoretical Planck blackbody spectrum (see **Planck's radiation law**). (The present best value for this temperature is 2.73 K, but it is still called three-degree radiation or the cosmic microwave background; see **cosmos: Microwave background radiation**.) The spectrum of this cosmic radio noise peaks at approximately one-millimetre wavelength, which is in the far infrared, a difficult region to observe; however, the spectrum has been well mapped at many wavelengths from that point through the radio region. Additional support for the big bang theory comes from the observed cosmic abundances of deuterium and helium. Normal stellar nucleosynthesis cannot produce their measured quantities, which fit well with calculations of production during the early stages of the big bang.

Surveys of the cosmic background radiation have indicated that it is extremely uniform in all directions (isotropic). Calculations have shown that it is difficult to achieve this degree of isotropy unless there was a very early and rapid inflationary period

The very earliest stages of the big bang are less well understood. The conditions of temperature and pressure that prevailed prior to the first microsecond require the introduction of theoretical ideas of subatomic particle physics. Subatomic particles are usually studied in laboratories with giant accelerators, but the region of particle energies of potential significance to the question at hand lies beyond the range of accelerators currently available. Fortunately, some important conclusions can be drawn from the observed cosmic helium abundance, which is dependent on conditions in the early big bang. The observed helium abundance sets a limit on the number of families of certain types of subatomic particles that can exist.

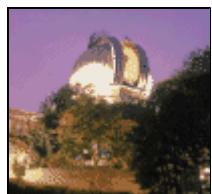
The age of the universe can be calculated in several ways. Assuming the validity of the big bang model, one attempts to answer the question: How long has the universe been expanding in order to have reached its present size? The numbers relevant to calculating an answer are Hubble's constant (i.e., the current expansion rate), the density of matter in the universe, and the cosmological constant, which allows for change in the expansion rate. In 2003 a calculation based on a fresh determination of Hubble's constant yielded an age of 13.7 billion \pm 200 million years, although the precise value depends on certain assumed details of the model used. Independent estimates of stellar ages have yielded values less than this, as would be expected, but other estimates, based on supernova distance measurements, have arrived at values of about 15 billion years, still consistent, within the errors. In the big bang model the age is proportional to the reciprocal of Hubble's constant, hence the importance of determining H as reliably as possible. For example, a value for H of 100 km/sec/Mpc would lead to an age less than that of many stars, a physically unacceptable result.

A small minority of astronomers have developed alternative cosmological theories that are seriously pursued. The overwhelming professional opinion, however, continues to support the big bang model.

Finally, there is the question of the future behaviour of the universe: Is it open? That is to say, will the expansion continue indefinitely? Or is it closed, such that the expansion will slow down and eventually reverse, resulting in contraction? (The final collapse of such a contracting universe is sometimes termed the "big crunch.") So-called **dark energy**, a kind of repulsive force that is now believed to be a major component of the universe, appears to be the decisive factor in predictions of the long-term fate of the cosmos. If this energy is a cosmological constant (as proposed in 1917 by **Albert Einstein** to correct certain problems in his model of the universe), then the result would be a "big chill." In this scenario, the universe would continue to expand, but its density would decrease. While old stars would burn out, new stars would no longer form. The universe would become cold and dark. The scenario changes, however, if the dark energy is not a cosmological constant. Accelerated expansion could end, and a big crunch would remain a possibility. A very speculative possibility is that the dark energy would cause a runaway acceleration of the expansion of the universe, ending in a "big rip." The dark (nonluminous) matter component of the universe, whose composition remains unknown, is not considered sufficient to close the universe and cause it to collapse; it now appears to contribute only a fourth of the density needed for closure.

An additional factor in deciding the fate of the universe might be the mass of **neutrinos**. For decades the neutrino had been postulated to have zero mass, although there was no compelling theoretical reason for this to be so. From the observation of neutrinos generated in the Sun and other celestial sources such as supernovas, in cosmic-ray interactions with Earth's atmosphere, and in particle accelerators, investigators have concluded that neutrinos have some mass, though only an extremely small fraction of the mass of an electron. Although there are vast numbers of neutrinos in the universe, the sum of such small neutrino masses appears insufficient to close the universe. (For additional discussion of the big bang theory, alternative cosmologies, and the age of the universe and its ultimate fate, see **cosmos: Cosmological models**.)

The techniques of astronomy



Astronomical observations involve a sequence of stages, each of which may impose constraints on the type of information attainable. Radiant energy is collected with **telescopes** and brought to a focus on a detector, which is calibrated so that its sensitivity and spectral response are known. Accurate pointing and timing are required to permit the correlation of observations made with different instrument systems working in different wavelength intervals and located at places far apart. The radiation must be spectrally analyzed so that the processes responsible for radiation emission can be identified.

The techniques of astronomy » Telescopic observations

Before **Galileo Galilei**'s use of **telescopes** for astronomy in 1609, all observations were made by naked eye, with corresponding limits on the faintness and degree of detail that could be seen. Since that time, telescopes have become central to astronomy. Having **apertures** much larger than the pupil of the human eye, telescopes permit the study of faint and distant objects. In addition, sufficient radiant energy can be collected in short time intervals to permit rapid fluctuations in intensity to be detected. Further, with more energy collected, a spectrum can be greatly dispersed and examined in much greater detail.

Optical telescopes are either **refractors** or **reflectors** that use lenses or mirrors, respectively, for their main light-collecting elements (objectives). Refractors are effectively limited to apertures of about 100 cm (approximately 40 inches) or less because of problems inherent in the use of large glass lenses. These distort under their own weight and can be supported only around the perimeter; an appreciable amount of light is lost due to absorption in the glass. Large-aperture refractors are very

The angular resolving power (or resolution) of a telescope is the smallest angle between close objects that can be seen clearly to be separate. Resolution is limited by the wave nature of light. For a telescope having an objective lens or mirror with diameter D and operating at wavelength λ , the angular resolution (in radians) can be approximately described by the ratio λ/D . Optical telescopes can have very high intrinsic **resolving powers**; in practice, however, these are not attained for telescopes located on Earth's surface, because atmospheric effects limit the practical resolution to about one arc second. Sophisticated computing programs can allow much-improved resolution, and the performance of telescopes on Earth can be improved through the use of adaptive optics, in which the surface of the mirror is adjusted rapidly to compensate for atmospheric turbulence that would otherwise distort the image. In addition, image data from several telescopes focused on the same object can be merged optically and through computer processing to produce images having angular resolutions much greater than that from any single component.

The atmosphere does not transmit radiation of all wavelengths equally well. This restricts astronomy on Earth's surface to the near ultraviolet, visible, and radio regions of the electromagnetic spectrum, with some relatively narrow "windows" in the nearer infrared. Longer **infrared** wavelengths are strongly absorbed by atmospheric water vapour and carbon dioxide. Atmospheric effects can be reduced by careful site selection and by carrying out observations at high altitudes. Most major optical **observatories** are located on high mountains, well away from cities and their reflected lights. Infrared telescopes have been located atop Mauna Kea (see **Mauna Kea Observatory**) in Hawaii and in the Canary Islands where atmospheric humidity is very low. Airborne telescopes designed mainly for infrared observations—such as (until 1995) on the **Kuiper Airborne Observatory**, a jet aircraft fitted with astronomical instruments—operate at an altitude of about 12 km (40,000 feet) with flight durations limited to a few hours. Telescopes for infrared, X-ray, and gamma-ray observations have been carried to altitudes of more than 30 km (100,000 feet) by balloons. Higher altitudes can be attained during short-duration rocket flights for ultraviolet observations. Telescopes for all wavelengths from infrared to gamma rays have been carried by robotic spacecraft observatories such as the **Hubble Space Telescope** and the Wilkinson Microwave Anisotropy Probe, while cosmic rays have been studied from space by the Advanced Composition Explorer.

Angular resolution better than one milliarcsecond has been achieved at radio wavelengths by the use of several **radio telescopes** in an array. In such an arrangement, the effective aperture then becomes the greatest distance between component telescopes. For example, in the **Very Large Array** (VLA), operated near Socorro, N.M., by the National Radio Astronomy Observatory, 27 movable radio dishes are set out along tracks that extend for nearly 21 km. In another technique, called **very long baseline interferometry** (VLBI), simultaneous observations are made with radio telescopes thousands of kilometres apart; this technique requires very precise timing.

Earth is a moving platform for astronomical observations. It is important that the specification of precise celestial coordinates be made in ways that correct for telescope location, the position of Earth in its orbit around the Sun, and the epoch of observation, since Earth's axis of rotation moves slowly over the years. Time measurements are now based on **atomic clocks** rather than on Earth's rotation, and telescopes can be driven continuously to compensate for the planet's rotation, so as to permit tracking of a given astronomical object.

The techniques of astronomy » Use of radiation detectors

Although the human eye remains an important astronomical tool, detectors capable of greater sensitivity and more rapid response are needed to observe at visible wavelengths and, especially, to extend observations beyond that region of the electromagnetic spectrum. **Photography** has been used in astronomy since the late 19th century and continues to be an essential tool (see **technology of photography: Astronomical photography**). Long-duration exposures may be needed to reveal faint objects. This integrative property of photography, however, smooths out rapid variations in radiation intensity; to study these variations, electronic methods must be used. Photography also provides an archival record. A photograph of a particular celestial object may include the images of many other objects that were not of interest when the picture was taken but that become the focus of study years later. When **quasars** were discovered in 1963, for example, photographic plates exposed before 1900 and held in the Harvard College Observatory were examined to trace possible changes in position or intensity of the radio object newly identified as quasar 3C 273. Also, major photographic surveys, such as those of the **National Geographic Society** and **Palomar Observatory**, can provide a historic base for long-term studies.

Photographic film converts only a few percent of the incident **photons** into images, whereas efficiencies of better than 80 percent can be achieved by any of several electronic methods of detection. The greater sensitivity and intrinsically rapid response of such methods are exploited for tracking exceedingly rapid variations in intensity. For example, **pulsars** that emit their radiation at millisecond intervals can be followed and their pulse shapes monitored. The arrival of individual photons can be recorded with **photomultiplier tubes** or with more advanced and sensitive detectors, such as **charge-coupled devices** (CCDs). Special photographic materials can be employed for the shortest infrared wavelengths, but semiconductor detectors that operate at very low (cryogenic) temperatures are used for wavelengths longer than a few micrometres. In detectors of this kind, the absorbed photons produce a minute temperature increase or a change in electrical resistance that is recorded as a signal; individual photons are not recorded. Reception of radio waves is based on the production of a small voltage in an antenna rather than on photon counting. Individual X-ray and gamma-ray photons possess sufficient energy to be detectable through the ionization that they produce.

Spectral analysis (see **spectroscopy**) involves measuring the intensity of the radiation as a function of wavelength or

see **telescope: Advances in auxiliary instrumentation**

The techniques of astronomy » Solid cosmic samples

As a departure from the traditional astronomical approach of remote observing, certain more recent lines of research involve the analysis of actual samples under laboratory conditions. These include studies of meteorites, rock samples returned from the Moon, cometary dust samples returned by space probes, and interplanetary dust particles collected by aircraft in the stratosphere or by spacecraft. In all such cases, a wide range of highly sensitive laboratory techniques can be adapted for the often microscopic samples. Chemical analysis can be supplemented with mass spectroscopy (see **mass spectrometry**), allowing isotopic composition to be determined. Radioactivity and the impacts of cosmic-ray particles can produce minute quantities of gas, which then remain trapped in crystals within the samples. Carefully controlled heating of the crystals (or of dust grains containing the crystals) under laboratory conditions releases this gas, which then is analyzed in a mass spectrometer. X-ray spectrometers, electron microscopes, and microprobes are employed to determine crystal structure and composition, from which temperature and pressure conditions at the time of formation can be inferred.

The techniques of astronomy » Theoretical approaches

Theory is just as important as observation in astronomy. It is required for the interpretation of observational data; for the construction of models of celestial objects and physical processes, their properties, and their changes over time; and for guiding further observations. Theoretical astrophysics is based on laws of physics that have been validated with great precision through controlled experiments. Application of these laws to specific astrophysical problems, however, may yield equations too complex for direct solution. Two general approaches are then available. In the traditional method, a simplified description of the problem is formulated, incorporating only the major physical components, to provide equations that can be either solved directly or used to create a numerical model that can be evaluated (see **numerical analysis**). Successively more-complex models can then be investigated. Alternatively, a computer program can be devised that will explore the problem numerically in all its complexity. Computational science is taking its place as a major division alongside theory and experiment. The test of any theory is its ability to incorporate the known facts and to make predictions that can be compared with additional observations.

Impact of astronomy

No area of science is totally self-contained. Discoveries in one area find applications in others, often unpredictably. Various notable examples of this involve astronomical studies. **Newton's laws of motion** and gravity (see also **celestial mechanics**; **Newton's laws of motion**) emerged from the analysis of planetary and lunar orbits. Observations during the 1919 solar eclipse provided dramatic confirmation of **Albert Einstein**'s general theory of relativity, which gained further support with the discovery and tracking of the binary pulsar designated PSR 1913+16. (See **relativity: Experimental evidence for general relativity** and **Gravitational waves**.) The behaviour of nuclear matter and of some elementary particles is now better understood as a result of measurements of neutron stars and the cosmological helium abundance, respectively. Study of the theory of **synchrotron radiation** was greatly stimulated by the detection of polarized visible radiation emitted by high-energy electrons in the supernova remnant known as the **Crab Nebula**. Dedicated particle accelerators are now being used to produce synchrotron radiation to probe the structure of solid materials and make detailed X-ray images of tiny samples, including biological structures (see **spectroscopy: Synchrotron sources**).

Astronomical knowledge also has had a broad impact beyond science. The earliest **calendars** were based on astronomical observations of the cycles of repeated solar and lunar positions. Also, for centuries, familiarity with the positions and apparent motions of the stars through the seasons enabled sea voyagers to navigate with moderate accuracy. Perhaps the single greatest effect that astronomical studies have had on our modern society has been in molding its perceptions and opinions. Our conceptions of the cosmos and our place in it, our perceptions of space and time, and the development of the systematic pursuit of knowledge known as the scientific method have been profoundly influenced by astronomical observations. In addition, the power of science to provide the basis for accurate predictions of such phenomena as eclipses and the positions of the planets and later, so dramatically, of comets has shaped an attitude toward science that remains an important social force today.

Michael Wulf Friedlander

Additional Reading » Overviews

Roger A. Freedman and William J. Kaufman III, *Universe*, 7th ed. (2005); Michael Zeilik, *Astronomy: The Evolving Universe*, 9th ed. (2002); and Michael A. Seeds, *Foundations of Astronomy*, 9th ed. (2007), are introductory texts.

Additional Reading » History

Traditional histories of astronomy include John Lankford (ed.), *History of Astronomy: An Encyclopedia* (1997); and John North,

The Norton History of Astronomy and Cosmology (also published as *The Fontana History of Astronomy and Cosmology*, 1994). David Leverington, *A History of Astronomy from 1890 to the Present* (1995), offers a good review of the period cited. Anthony F. Aveni, *Empires of Time: Calendars, Clocks, and Cultures*, rev. ed. (2002), provides an introduction to archaeoastronomy.

Additional Reading » Guides and handbooks

Ian Ridpath (ed.), *Norton's Star Atlas and Reference Handbook, Epoch 2000.0*, 20th ed. (2004), is a popular atlas with explanatory material. Stephen James O'Meara, *The Messier Objects* (also published as *The Messier Objects Field Guide*, 1998), provides a guide to the objects in this famous catalog. Martin Mobberley, *The New Amateur Astronomer* (2004), is a general guide to telescopes and observing. Listings of observational information are found in U.S. Naval Observatory Nautical Almanac Office and Great Britain Nautical Almanac Office, *The Astronomical Almanac* (annual); and Royal Astronomical Society of Canada, *The Observer's Handbook* (annual). Kenneth R. Lang, *A Companion to Astronomy and Astrophysics: Chronology and Glossary with Date Tables* (2006), is a dictionary of technical terms, with names of scientists, values of astronomical quantities, and brief historical notes, and *Astrophysical Formulae*, 3rd ed. rev. and enlarged, 2 vol. (1999), is a comprehensive reference source with extensive formulas and background data. Arthur N. Cox (ed.), *Allen's Astrophysical Quantities*, 4th ed. (2000), is a standard reference updated every few years.

Additional Reading » Current knowledge

Works dealing with forefront areas of research and directed to the nonspecialist include F.A. Aharonian, *Very High Energy Cosmic Gamma Radiation* (2004); Paul Halpern and Paul Wesson, *Brave New Universe: Illuminating the Darkest Secrets of the Cosmos* (2006); D.A. Lorimer and M. Kramer, *Handbook of Pulsar Astronomy* (2005); James B. Kaler, *Extreme Stars: At the Edge of Creation* (2001); A.C. Fabian, K.S. Pounds, and R.D. Blandford, *Frontiers of X-ray Astronomy* (2004); Andreas Eckart, Rainer Schödel, and Christian Straubmeier, *The Black Hole at the Center of the Milky Way* (2005); and Simon Singh, *Big Bang: The Origin of the Universe* (2004).

Additional Reading » Periodicals

Up-to-date reviews of specialized topics are found in the *Annual Review of Astronomy and Astrophysics* and *Annual Review of Earth and Planetary Sciences*. Their first chapters are often devoted to reminiscences by major scientists. Major professional journals include *The Astronomical Journal* (10/year) and *The Astrophysical Journal* (3/month), both published for the American Astronomical Society; the *Monthly Notices of the Royal Astronomical Society* (3/month); and *Astronomy and Astrophysics* (4/month), managed by the European Southern Observatory for a consortium of European astronomical societies. An excellent publication is *Sky and Telescope* (monthly), directed to the serious amateur astronomer and still of interest to the professional.

Michael Wulf Friedlander

Related Articles

Aspects of this topic are discussed in the following places at Britannica.

Assorted References

- **calendar systems** (*in calendar: Standard units and cycles*; *in calendar: Adoption in various countries*)
- **cartography** (*in map: 18th century to the present*)
- **observation of Sun** (*in Sun: History of observation*)
- **relation to astrology** (*in divination: Inductive divination*)
- **significance of eclipses** (*in eclipse: Uses of eclipses for astronomical purposes*)
- **spectroscopy** (*in spectroscopy: Applications*)
- **star identification** (*in astronomical map: Nature and significance*)
- **time measurement** (*in time: Time units and calendar divisions*)
- **work of Cannon** (*in Cannon, Annie Jump*)

in physical science: Ancient Middle Eastern and Greek astronomy *in physical science: Astronomy* *in physical science: Celestial mechanics and astronomy* *in physical science: Astronomy*

- **development in**

- **early humans** (*in Cosmos: Earliest conceptions*)
- **Egypt** (*in Egypt, ancient: Sources, calendars, and chronology*; *in Middle East, ancient: Science and law*)
- **Greece** (*in Hellenistic Age: Science and medicine*; *in mathematics: Applied geometry*; *in science, history of: Aristotle and Archimedes*)
- **India** (*in India: Society and culture*)
- **Islamic civilizations** (*in education: Organization of education*)
- **Maya civilization** (*in Dresden Codex*; *in pre-Columbian civilizations: The Maya calendar and writing system*)
- **Mesopotamia** (*in Mesopotamia, history of: The achievements of ancient Mesopotamia*; *in Mesopotamia, history of: Ashurbanipal (668–627) and Shamash-shum-ukin (668–648)*; *in priesthood: The ancient Middle East*)

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- **mathematical astronomy** (*in mathematics: Mathematical astronomy*; *in mathematics, South Asian: The role of astronomy and astrology*)
- **natural philosophy** (*in science, history of: Precritical science*)
- **trigonometry** (*in trigonometry*)

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- **Eudoxus of Cnidus** (*in Eudoxus of Cnidus*)
- **Hipparchus** (*in Hipparchus: Lover of truth*)
- **Kepler** (*in Kepler, Johannes*)
- **Mei Wending** (*in Mei Wending*)
- **Plato** (*in metaphysics: Metaphysics as knowledge of the supersensible*)
- **Pythagoras** (*in Pythagoreanism: Astronomy*)

technological aspects

- **astronomical camera** (*in photography, technology of: Astronomical photography*; *in meteor and meteoroid: Measurement of meteoroid orbits*)
- **radio telescopes** (*in telescope: Radio telescopes*)

External Web sites

Articles from Britannica encyclopedias for elementary and high school students.

astronomy - Children's Encyclopedia (Ages 8-11)

One of the oldest sciences in the world, astronomy is the study of all objects and matter outside the Earth's atmosphere. These include the sun, Moon, planets, stars, galaxies, and other matter in the universe.

astronomy - Student Encyclopedia (Ages 11 and up)

Since the beginnings of humankind people have gazed at the heavens. Before the dawn of history someone noticed that certain celestial bodies moved in orderly and predictable paths, and astronomy—an ancient science—was born. Yet some of science's newest discoveries have been made in this same field, which includes the study of all matter outside Earth's atmosphere. From simple observations of the motions of the sun and the stars as they pass across the sky, to advanced theories of the exotic states of matter in collapsed stars, astronomy has spanned the ages.

This topic is discussed at the following external Web sites.

The Barnard-Seyfert Astronomical Society

Resources from the Nashville, Tennessee astronomical organization. Provides membership news and event schedules and links to astronomy and weather resources, as well as an image gallery including Hubble space telescope photos. Also provides tracking information for visible space shuttle flights and satellite paths over Tennessee.

The Yakima Astronomical Society

Astronomy club located in Selah, Washington.

Orwell Astronomical Society - astronomy

"Information on this Ipswich, England-based astronomical organization dedicated to popularize the science of astronomy among people. Covers its historical background, mission, activities, observation facilities, workshops, publications, and includes photographs."

Astronomy in Japan

Collection of articles on many aspects of Japanese astronomy: history, legends and myths about the stars and sky, ancient (Japanese and Chinese) calendar and time systems, astronomical nomenclature, and the activities and discoveries of amateur astronomers. Includes links to other English-language pages for astronomical data, Japanese amateur astronomy, and Japanese observatories.

Sky and Telescope

Web component of the magazine, Sky and Telescope, published from Cambridge, Massachusetts, U.S., on astronomy. Offers articles covering news, photography, and CD imaging, tips on stargazing, sights, and reference materials. Also features an online store.

SciCentral

Extensive directory of more than 50,000 sites in the sciences. Includes listings in the biological sciences, the physical and chemical sciences, health science, engineering, and earth and space sciences. Additional directories on women and minorities in science, science in the news, government agencies, institutions and academic resources, professional resources, and K-12 education are available.

Astronomy and Telescopes

Interactive math and science activities for elementary and middle school students. Covers an observation of the planets and moon, the Pythagorean theorem, exploration of the Sun's properties, and space missions.

Seasky.org - The Sky

The Constellations and Their Stars

Astronomy Among Ancient Tombs and Relics in Asuka, Japan

Illustrated information on the alignment sites, and astronomical observatory points in this area.

Hall of Astronomers

Profiles of prominent astronomers, astrophysicists, and mathematicians. Includes an astronomy dictionary, and a weekly newsletter.

Astronomy for Kids

Illustrated information on the solar system and the cosmological bodies, for children. Includes a related glossary and brief notes on astronauts.

Sea and Sky - The Sky

How the Greeks Used Geometry to Understand the Stars

Astronomy Sight

Vast resources on this intriguing branch of science. Contains news and information on our universe, constellations, planets, comets, telescopes and deep space, and suggests studies, books and programs. Includes an interactive moon phase calendar and list of astronomical terms.

Cosmobrain

Collection of links to sites providing information on astronomy and astrophysics. Covers topics such as planets, comets, artificial satellites, cosmology, and telescopes. Also features an online bookstore on the subject.

HubbleSite

Collection of outstanding images and data gathered from the Hubble Space Telescope. Includes a photo depicting Jupiter's surface after Comet Shoemaker-Levy 9 crashed into it; accompanying text explains that the comet fragments

Amateur CCD Astronomy

Collection of astrophotographs by Richard Jacobs. Includes details of equipment used, solar system, planetary nebula, star clusters, and galaxies.

Astronomy Now Online

Online version of this monthly magazine. Provides news in the fields of astronomy and space science.

Windows to the Universe

Students for the Exploration and Development of Space - The Messier Catalog

AmSky: The Online Magazine for Amateur Astronomy

E-zine on astronomy. Includes articles from present and archived issues along with related news items.

Astrophotography

Collection of photographs of astronomical objects. Includes guidelines on editing techniques.

The Astronomical Society of New South Wales

Profile of this Australian organization. Contains articles and details on its projects, facilities, conferences, and events. Includes a picture gallery, newsletter, and briefs on its observatory.

The Astronomical Society of Singapore - Astrophotography Gallery

Greek Astronomy

Essay on the history of observation and discovery of the Earth, Moon, Sun, and universe. Covers various ancient calendars and the contributions of astronomers. Includes links to biographies of Aristotle, Pythagoras, Ptolemy, Democritus, Eudoxus, and Aristarchus.

The Catholic Encyclopedia - Astronomy

Essay in the Catholic Encyclopedia explaining this branch of physics dealing with the study of stars. Covers prehistoric, Greek, descriptive, sidereal, and theoretical astronomy, discoveries, celestial photography, and astrophysics.

Astronomy Magazine

Official Site of the Peoria Astronomical Society

Arizona, U.S.-based scientific organization involved in promoting learning about astronomy. Features information on star names, constellations, planets, Messier objects, black holes and news of upcoming cosmic events. Also provides a three-dimensional star map, membership information, and a newsletter.

Eric Weisstein's World of Science

University of Tennessee - Astronomy 161: The Solar System

Astronomy Notes

Basic educational information on this subject. Features sections on the history of astronomy, methods of discovering scientific truth, Newton's laws of gravity, Einstein's theory of relativity, and cosmology. Also includes a glossary of astronomical terms.

Amazing Space

National Astronomy and Ionosphere Center - Arecibo Observatory

Enchanted Learning - Zoom Astronomy

Illustrated educational resource on the solar system, asteroids, stars, and comets. Includes classroom activities, tutorials, an astronomy glossary, quizzes, and information on related topics.

The Planetary Society

Space Images

USGS Astrogeology: Gazetteer of Planetary Nomenclature

KidsAstronomy.com

The New Georgia Encyclopedia - Astronomy

Nick Strobel - Astronomy

ThinkQuest - Astronomy

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